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A REVIEW OF NON-DESTRUCTIVE AND DESTRUCTIVE RESIDUAL STRESS MEASUREMENTS

G. ROY and W.R. TYSON
ENGINEERING AND METAL PHYSICS SECTION

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INTRODUCTION

1. Description of Residual Stresses

Residual stresses, frequently called "locked-in" stresses or "internal" stresses, refer to the stresses existing in a component part or assembly free from external loads. Problems associated with these stresses, mainly the contribution they can make to premature failure of metallic structures, have been recognized by engineers for several decades. Residual stresses can be produced in metals in various ways which may be classified - depending on the processes involved - into two groups:

- a) Processes causing a structural member to undergo non-uniform, permanent dimensional change. Residual stresses are then distributed through appreciable volumes and referred to as "macrostresses".
- b) Processes causing deformation within grains or between grains in a structural member. Residual stresses are then distributed through microscopic volumes only and are referred to as "microstresses".

The assembly of component parts into a structure may relieve some residual stresses but, usually, many additional stresses are introduced. On the other hand, suitable internal stresses may increase the life of a structure. Locked-in stresses are helpful if they oppose the working stresses and are harmful if they add to the working stresses. Therefore, it is important to know the magnitude and direction of internal stresses.

2. Determination of Residual Stresses

It is difficult to determine the magnitude and direction of internal stresses but several successful methods have been devised. These may be classified as:

- a) Mechanical
- b) Physical
- c) Chemical

Widely used mechanical methods involve the disturbance of an object's stress equilibrium through some mechanical means and the measurement of the resultant elastic deformations.

Physical methods are based on observations of certain physical phenomena using appropriate instruments.

There is at present only one chemical method that seems to be useful; it is based upon the combined effects of a corrosive environment and a static tensile stress; it is called the "Stress Corrosion Method".

The available mechanical methods may, in turn, be classified into four groups:

- a) Layer removal
- b) Boring and turning
- c) Hole drilling and trepanning
- d) Parting-out

The available physical methods may be classified into four groups as well:

- a) Electromagnetic
- b) Ultrasonic
- c) X-ray diffraction
- d) Indentation

In this presentation, the term "method" means a general procedure adopted to determine residual stress state, and the term "technique" is reserved to mean a manner of execution (including the technical details) of the procedure.

Mechanical methods, to release the residual stresses, involve experimental procedures called relaxation techniques. By necessity, however, all these techniques are to some degree destructive, and herein lies their major disadvantage. Also, there is always a risk of additional residual stresses being introduced as material is removed, but as long as this is understood, in general the experimental procedure can be adjusted to avoid or minimize these effects.

It is also necessary to determine the precision with which residual stresses are to be determined. The technique chosen for measuring the dimensional changes used to determine the residual stresses is important and depends on the desired precision. There are associated specific relaxation and/or measurement techniques with any particular method, see Table 1.

The choice of the method depends on the geometry of the specimen, the type and location of the stress to be measured, the desired precision and the available equipment. Table 2 may be of assistance in making a suitable selection.

BRIEF REVIEW OF METHODS OF RESIDUAL STRESS MEASUREMENTS

1. Layer Removal

Using this method the residual stresses are determined by measuring their effect on the deformation of a specimen; a layer of material is removed and the stress in that layer is determined from the strain changes produced in the remainder of the specimen. The stress distribution through the specimen may be accurately determined, since extremely thin layers may be removed, but the part is completely destroyed. When the distribution of the stresses through the entire part thickness is desired, two series of layers, called primary and secondary, are removed from two opposite faces of a specimen; an example of this method is shown in Fig. 1. Relaxation techniques of "grinding" and "slicing" may be used in this method. In the example, grinding is commenced at the surface opposite to the surface of prime interest; the layers removed are relatively thick. After removal of each layer the specimen bends and the arc height is measured, see Fig. 2. Following this, the secondary layers (much thinner than the primary layers) are removed by slicing from the surface of interest, and as before, curvature measurements are made. The curvature change produced by these procedures is utilized to measure the stress gradient. The method is well described in (1) and (2).

2. Boring and Turning

This is a specialized layer removal method and is applied particularly to circular cylindrical sections. By removing layers from the bore or the outer surface and measuring the longitudinal and tangential strain changes on the surface opposite to that on which layers are removed, the tangential, radial and longitudinal stress distribution along a radius may be determined.

If the complete stress distribution is desired, then the method of removing primary and secondary layers may be used, see (3).

3. Hole Machining and Trepanning

a) Hole machining

Application of this method requires the machining of a hole in the specimen, and the simultaneous measurement of the surface strains in the vicinity of that hole. At present, this is probably the most suitable general purpose method for the measurement of residual stresses both in the laboratory and in site applications, because the structural component is damaged only slightly. Most of this review is therefore devoted to development and applications of this method; see the section titled, "Hole Drilling Technique".

b) Trepanning

This method accomplishes relaxation by removing a plug of material, to which strain gauges have been adhered. The plug is removed either by drilling a series of overlapping holes, see Fig. 3, or by using a rotary cutter or electrical discharge machine, see Fig. 4 and 5, respectively. If the directions of the principal stresses are not known, the strain gauges are arranged in rosette form. Calculation of the residual stresses is based on the initial and final strain-gauge readings. The method can be reliable when the stresses are fairly uniform over the area to be measured, see (4).

4. Parting-out

This method generally requires the removal of a coupon from the region of interest in the parent part as a first step to determining residual stresses by one of the methods already discussed. The type of coupon to be parted-out depends on the state of stress to be measured and on other factors such as parent part geometry, see Fig. 6. Usually plate or beam coupons are cut to measure the uniaxial and biaxial stresses. If the principal directions of the residual stresses are not known, plates must be parted out; if the stresses are uniaxial, one beam is needed; if biaxial, two. A good description of the method may be found in (5).

5. Electromagnetic

Electromagnetic methods take advantage of magnetic domain phenomena and are therefore, limited to ferromagnetic materials. They make use of the fact that the magnetic properties of many ferromagnetic materials are sensi-

tive to stress, to such an extent that stress may be ranked with field strength and temperature as one of the primary factors affecting magnetization. When a magnetic body is magnetized, it changes its dimensions; this phenomenon is called "magnetostriction." Thus, the effect of strain or stress on magnetization is closely related to magnetostriction. For example, when nickel is magnetized, it contracts by a small fraction of its original length, whereas 68 Permalloy increases in length, see Fig. 7. Nickel and 68 Permalloy are representatives of materials with negative and positive magnetostriction, respectively. Tension increases the magnetization of a body having positive magnetostriction, and decreases the magnetization when magnetostriction is negative.

There are two electromagnetic methods of residual stress measurement gradually gaining use: the "Barkhausen method" and the "magnetic method".

5.1 Barkhausen

This method measures the number and magnitude of abrupt reorientations made by the magnetic domains in a ferromagnetic material subject to an electric field. In 1919, Barkhausen discovered this effect and interpreted it as demonstrating that the magnetization of iron proceeds by steps and not in a continuous manner. The technique serving to detect and analyze these changes is called the "Barkhausen noise analysis technique". Reorientation of domains is detected as pulses of random amplitude and duration, heard in ear phones or loud-speakers as a succession of clicks. These clicks can be roughly described as "noise". Because residual stresses have an effect on noise, the stress distribution in the material and its magnitude may be quantified. There have been a few successful applications of this method, but it is restricted by the need for calibration with a nearly identical specimen. Also, further research must be done to investigate the effect of micro-structure on Barkhausen noise, see (6).

5.2 Magnetic

In this method, the reversible effective permeability is measured over a range of frequency of an applied alternating field. When the magnetic flux in a conducting medium changes with time, eddy or Foucault currents are generated within the material.

Eddy currents prevent the field from penetrating the interior of the material; thus, magnetic induction decreases from the surface toward the

interior. The flux-carrying capacity of the material depends on its dimensions, permeability ($\mu = \frac{B}{H}$, where B is induction and H is field strength), resistivity, and on the frequency of alternation of the magnetic field. It may be calculated accurately and expressed in terms of the reversible effective permeability, μ_{eff} , defined as the ratio of the amplitude of the induction, ΔB , to the amplitude of the applied field strength, ΔH . The permeability is stress-sensitive because of the phenomenon of magnetostriction. This dependence was utilized to find residual stresses in the outer portions of nickel and steel rods (7): magnetic stress measurements were determined from inductance measurements, see Fig. 8.

6. Ultrasonic

A number of velocity-related phenomena are used to measure stress effects by ultrasound.

The constitutive equation of an elastic material is of the form

$$\sigma = f(\epsilon) \quad \text{Eq 1}$$

where σ is the stress tensor, ϵ is the strain tensor, and f is the response function. The simplest form of this dependence, in a one-dimensional case, is Hooke's law of elasticity

$$\sigma = E\epsilon \quad \text{Eq 2}$$

where E is Young's modulus. If the response function, f , is assumed to be analytic, containing higher order terms, we have an expansion, see (8),

$$\sigma = E\epsilon + F\epsilon^2 + G\epsilon^3 + \dots, \quad \text{Eq 3}$$

linear term non-linear terms

Deviation from Hooke's law, in the form of non-linear terms in Eq 3, is called an anharmonic effect. Because non-linearity exists in the stress-strain relationship of all materials, the elastic constant of a solid (the slope E of the stress-strain curve) changes under applied stress, see Fig. 9.

The velocity of a sound wave in a medium is given by, $v = \sqrt{\frac{E}{\rho}}$, where ρ is the density of the medium. Velocity changes with stress and measuring

velocity changes as a function of stress is the basis of all ultrasonic methods (9). A shear wave, entering a stressed isotropic solid, resolves itself into two components polarized parallel to the principal stress directions. Because the waves propagate with different velocities depending on the magnitude of the applied stresses, these stresses may be deduced from the difference in velocities. This is the basis of the birefringence technique.

The surface wave dispersion technique is based on measurement of wave velocity as a function of depth. This is achieved by using high-frequency waves, which penetrate into the surface only to a distance approximately equal to a wavelength. Hence, by measuring the frequency dependence of the velocity, it is possible to deduce the depth dependence of velocity and hence stress.

By the use of specially cut quartz crystals and appropriate electronic equipment, a sound wave with a frequency between less than one to several megahertz is propagated through a metal specimen and the time of flight measured.

It is known, however, that besides stress-induced elastic strain there are other characteristics of metals that affect velocity of ultrasound. For example, birefringence is also produced by microstructural anisotropy. Although the effect has not been evaluated quantitatively, work on the problem is worthwhile because these methods are promising for three-dimensional non-destructive stress measurements.

7. X-Ray Diffraction

Stress measurement by means of X-rays is based on change of the interplanar spacing of atomic planes within a specimen when subjected to stress. Elastic strain and hence residual stress can be calculated from atomic spacing measurements. The lattice spacing can be calculated by the well known Bragg equation when the diffracted angle of an incident beam of X-ray is measured either by a back reflection camera or by a suitable diffractometer, see Fig. 10. Originally, it was necessary to take measurements in both the stressed and unstressed state. Later the technique was refined by making two or more X-ray exposures at different angles of incidence, ψ , between the incident beam and specimen surface thus avoiding the need to measure the lattice parameter in the stress free state. The method is often referred to as the $\sin^2\psi$ technique (10). X-rays have been adopted more widely

in recent years for stress measurement and are being used in a variety of situations (10).

8. Indentation

This method, commonly called the "Hertzian hardness method", depends on determining residual stresses by making hardness measurements. In practice it involves the measurement of the load necessary to cause plastic flow when imposed upon a spherical indenter (Fig. 11). This load is a measure of the residual surface stresses, since flow will occur when the superimposed values of the residual stresses and those produced by the indenter reach certain critical values. The method was applied by Underwood for measuring the direction and magnitude of residual stress in metals. He employed optical interference to analyze the nonsymmetrical surface deformation around a shallow spherical indentation (11).

9. Stress Corrosion

Some corrodents cause cracking (called "stress corrosion cracking", SCC) on the surface of certain alloys in the presence of stress from applied loads or residual strains, and thus, may be used to detect stresses. The method is based on the fact that the time to cracking is dependent on the level of tensile stress. The tensile stress must exceed a certain threshold value or cracking does not occur. In terms of fracture mechanics, the rate of crack growth depends on the magnitude of K_I (stress intensity factor in mode I); the threshold value of stress intensity is designated K_{ISCC} . For stress intensities below K_{ISCC} crack growth does not occur, but if the initial value of K_I is above K_{ISCC} then crack growth and eventual failure occurs, see Fig. 12. Stress corrosion cracking results in a nonductile type of failure. There are many combinations of common alloys and corrodents that cause SCC, e.g., aluminum alloys and sea-water, copper alloys and ammonia, and stainless steel and sulfuric acid solution. For a more complete list of corrosive agents and alloys see (13). The analysis of stress-corrosion cracking by fracture-mechanics methods is treated in (14). Though the method is qualitative as yet for residual stress detection, reproducible results may be obtained. The simplicity of the method recommends its further development and application.

HOLE-MACHINING METHOD

To measure residual stresses it is necessary to choose method and technique. The choice should take into consideration all factors likely to influence the accuracy of a measurement. At a recent symposium organized by the Canadian Electrical Association (CEA), the current state-of-the-art in this field was reviewed. A summary of the presentations is given in the Appendix. The method receiving most attention was the hole machining method, which is elaborated in detail in this section.

1. Theoretical and Numerical Approaches

A method for measuring residual stress in structures of all kinds should be non-destructive. However, totally non-destructive methods do not always give a complete and accurate picture of the stress distribution. The hole-machining method is the least destructive of the mechanical methods, and offers a simple and reasonably accurate procedure permitting evaluation of residual stresses with a minimum of structural damage.

Mathar first suggested this method in 1933 (22). A relatively small hole is drilled normal to the surface of the specimen at the point of interest and the resulting deformation in the surface produced by relaxation of the residual stresses is measured by strain gauges. When the stressed material is removed, the surrounding material must readjust its stress state to attain equilibrium, see Fig. 13. When the hole is drilled the stress normal to the surface of the hole decreases to zero at the edge of the hole and the remaining stress is modified in the manner shown in the figure. The change in strain accompanying the stress changes shown by the shaded area is indicated by the strain gauge.

The relationship between the relieved stresses and the measured strain relaxation can be found analytically if certain assumptions regarding the nature of the locked-in stresses are made. In general, these stresses are assumed to be biaxial. The surface deformations approach a limiting value with increasing hole depth. This value, ϵ_0 in Fig. 14 (a), has been found to occur at a hole depth varying from one to two times the hole diameter. In the presence of a uniform stress field, the problem is to find the relationship between ϵ_0 and the magnitude of the stress. In the case of a non-uniform stress field the increments of surface strain, $\Delta\epsilon_z$ in Fig. 14(b), must be correlated with increments in hole depth, Δz , and the stress σ_z at depth z .

When a hole of small diameter is drilled in a region initially containing uni-axial residual stress, i.e., biaxial residual stress where one of the stresses equals zero, the relieved strains may be plotted as in Fig. 15. In the general case where both stresses are non-zero a three-element strain rosette is required. For any given value of σ_R , see Fig. 13, the strain changes detected by the gauges will vary with the distance "x". The drilled hole, therefore, must be the same distance from each of the three elements of the rosette; Fig. 16 shows a rosette specially designed for this purpose.

If it is assumed that residual stresses vary uniformly with depth from the surface, and further (22) that the stress and strain distributions around a hole of depth equal to the diameter are similar to those around a through-the-plate hole in uniformly-stressed infinite plate, see Fig. 17, the theoretical solution (23) for the radial strain relaxation is:

$$\epsilon_r = (A + B\cos 2\alpha) \sigma_p + (A - B\cos 2\alpha) \sigma_q$$

where

$$A = - \frac{1 + \nu}{2E} \frac{R_o^2}{R}$$

and

$$B = - \frac{1 + \nu}{2E} \frac{4}{1 + \nu} \frac{R_o^2}{R} - 3 \frac{R_o^4}{R^3},$$

where σ_p and σ_q are principal stresses

R_o is hole radius

R is distance from the center of the hole, $R > R_o$

E is Young's modulus

ν is Poisson's ratio

α is angular coordinate measured anticlockwise from the σ_p direction, see Fig. 18.

In order to determine the principal residual stresses and their directions with respect to any reference axis, three independent strain measurements must be made. Let ϵ_1 , ϵ_2 and ϵ_3 be the radial strains measured by gauges as shown in Fig. 19. Utilizing the above relationship the following equations may be obtained (24),

$$\epsilon_3 = \sigma_p (A + B\cos 2\theta) + \sigma_q (A - B\cos 2\theta),$$

$$\epsilon_2 = \sigma_p (A - B \sin 2\theta) + \sigma_q (A + B \sin 2\theta),$$

$$\epsilon_1 = \sigma_p (A - B \cos 2\theta) + \sigma_q (A + B \cos 2\theta),$$

where

$$\theta \leq \frac{\pi}{2}.$$

Inverting these equations, the magnitude and direction of the two principal stresses may be expressed in terms of the measured radial strains as follows,

$$\sigma_p = \frac{\epsilon_1 + \epsilon_3}{4A} - \frac{(2\epsilon_2 - \epsilon_1 - \epsilon_3)^2 + (\epsilon_1 - \epsilon_3)^2}{4B}^{1/2}$$

$$\sigma_q = \frac{\epsilon_1 + \epsilon_3}{4A} + \frac{(2\epsilon_2 - \epsilon_1 - \epsilon_3)^2 + (\epsilon_1 - \epsilon_3)^2}{4B}^{1/2}$$

$$\theta = \frac{1}{2} \tan^{-1} \frac{2\epsilon_2 - \epsilon_1 - \epsilon_3}{\epsilon_3 - \epsilon_1},$$

where θ is the angle measured anticlockwise from the σ_p direction to gauge number 3. Rearranging the right hand sides of the above expressions (25),

$$\sigma_p = A_1(\epsilon_3 + \epsilon_1) - B_1 \left((\epsilon_2 - \epsilon_3)^2 + (\epsilon_2 - \epsilon_1)^2 \right)^{1/2}$$

$$\sigma_q = A_1(\epsilon_1 + \epsilon_1) + B_1 \left((\epsilon_2 - \epsilon_3)^2 + (\epsilon_2 - \epsilon_1)^2 \right)^{1/2}$$

where

$$A_1 = - \frac{E}{2(1 + \nu)} \left(\frac{R}{R_0} \right)^2 = \frac{1}{4A}$$

$$B_1 = \frac{-0.5 \sqrt{2} E}{3(1 + \nu)} \frac{R}{R_0}^2 = \frac{\sqrt{2}}{4B}$$

It is assumed that these expressions for A and B or A_1 and B_1 for a through hole may be used as a first approximation to the constants for a blind hole.

The constants A_2 and B_2 for a blind hole are usually determined from measurements of known stress fields as follows. The principal stress σ_q is made to equal zero, and a known stress, σ , is applied in the direction of the x-axis of the strain-gauge coordinate system, i.e., $\sigma_p = \sigma$, see Fig. 20; δ is then made equal to zero. Under these conditions (26)

$$A_2 = \frac{\epsilon_1 + \epsilon_3}{2\sigma}$$

and

$$B_2 = \frac{\epsilon_1 - \epsilon_3}{2\sigma}$$

If a measurement of strain over a finite gauge area rather than at a point is included in calculations for A and B (theoretical factors for through-thickness hole), the solution for A and B becomes

$$A_3 = \frac{R_o^2(1 + \nu)}{E \times \text{AREA}} (\gamma_2 - \gamma_1)$$

$$B_3 = \frac{R_o^2(1 + \nu)}{E \times \text{AREA}} \left[\frac{2(1 - \nu)}{1 + \nu} (\gamma_2 - \gamma_1) + \sin 2\gamma_2 - \sin \gamma_1 \right]$$

$$- \frac{1}{8} \frac{R_o^2}{R_2^2} (2 \sin 2\gamma_2 + \sin 4\gamma_2)$$

$$+ \frac{1}{8} \frac{R_o^2}{R_1^2} (2 \sin 2\gamma_1 + \sin 4\gamma_1)$$

where "AREA" is the area of each strain gauge element and R_1 , R_2 , γ_1 and γ_2 are shown in Fig. 21 (27). The measured constants A_2 and B_2 should approach these values at large hole depths.

The constants A_2 and B_2 are functions of the material constants E and ν . If these material constants could be separated out, then equations for σ_p , σ_q and δ would apply to any elastic, isotropic material. This has led some authors (16, 26 and 28), to introduce material independent constants k_1 and k_2 such that

$$\epsilon_p = \frac{k_1}{E} \tau_p - \nu \frac{k_2}{E} \tau_q$$

and

$$\epsilon_q = \frac{k_1}{E} \sigma_q - \nu \frac{k_2}{E} \sigma_q,$$

where ϵ_p and ϵ_q are the strains in the direction of the principal stresses, σ_p and σ_q . The constants A_2 and B_2 may then be evaluated in terms of the general constants k_1 and k_2 and material constants E and ν as follows,

$$A_2 = \frac{1}{2E} (k_1 - \nu k_2)$$

and

$$B_2 = \frac{1}{2E} (k_1 - \nu k_2)$$

Thus, if E and ν are known, one calibration to determine k_1 and k_2 suffices for all elastic isotropic materials. Beaney (16) found that the ratio $\nu k_2/k_1$ has an almost fixed value of 0.3 for a wide class of materials, and this led him to the following expressions for the principal stresses

$$\sigma_p = -\frac{1}{k_1} \frac{E}{2} \frac{\epsilon_1 + \epsilon_3}{1 - \frac{\nu k_2}{k_1}} + \frac{1}{1 + \frac{\nu k_2}{k_1}} (\epsilon_3 - \epsilon_1)^2 + [(\epsilon_1 + \epsilon_3) - 2\epsilon_2]^2$$

$$\sigma_q = -\frac{1}{k_1} \frac{E}{2} \frac{\epsilon_1 + \epsilon_3}{1 - \frac{\nu k_2}{k_1}} - \frac{1}{1 + \frac{\nu k_2}{k_1}} (\epsilon_3 - \epsilon_1)^2 + [(\epsilon_1 + \epsilon_3) - 2\epsilon_2]^2$$

$$\theta = \frac{1}{2} \tan^{-1} \frac{(\epsilon_1 + \epsilon_3) - 2\epsilon_2}{\epsilon_3 - \epsilon_1}.$$

These equations are identical in form to those used to calculate stresses in a biaxial stress field from the strains recorded by a rectangular rosette (30),

$$\sigma_p = \frac{E}{2} \frac{\epsilon_1 + \epsilon_3}{1 - \nu} + \frac{1}{1 + \nu} \sqrt{(\epsilon_3 - \epsilon_1)^2 + [(\epsilon_1 + \epsilon_3) - 2\epsilon_2]^2}$$

$$\sigma_q = \frac{E}{2} \frac{\epsilon_1 + \epsilon_3}{1 - \nu} + \frac{1}{1 + \nu} \sqrt{(\epsilon_3 - \epsilon_1)^2 + [(\epsilon_1 + \epsilon_3) - 2\epsilon_2]^2}$$

The ratio $\nu k_2/k_1$ replaces Poisson's ratio ν , and $-1/k_1$ is an overall calibration factor depending on the distance of the gauges from the edge of the hole and on the geometry of the hole. These two sets of expressions for σ_p and σ_q are similar because the distribution of strains is of the same form for the two cases. Schajer obtained an even better result than Beaney for $\nu k_2/k_1$ (27). He noticed that for changes in Poisson's ratio in the range 0.25 to 0.35, $\nu k_2/k_1$ varies from 0.32 to 0.27; furthermore, he proposed alternative definitions of material-independent constants which overcome the theoretical shortcomings of constants k_1 and k_2 ,

$$C_1 = \frac{2EA'_3}{1 + \nu}, \quad C_2 = 2EB'_3$$

where A'_3 and B'_3 are the constants when the finite gauge area and finite hole depth are included in the analysis. Both C_1 and C_2 vary by less than 2% for changes in Poisson's ratio in the range 0.25 to 0.30 (27).

The hole-drilling technique has been adopted by some researchers, see (28) and (29), to assess stress variation with depth. It is assumed, for a uniaxial stress field, that the measured change in strain for a small hole depth increment is proportional to the stress at that depth,

$$\Delta\epsilon_Z(\alpha) = K_Z(\alpha)\sigma_Z\Delta Z,$$

where σ_Z is the stress at depth Z , α is the angle between the stress axis and a radial direction from the hole, $\Delta\epsilon_Z(\alpha)$ is the radial strain at a given radial distance caused by drilling a distance ΔZ at a depth Z , and $K_Z(\alpha)$ is a proportionality factor which must be determined experimentally, see Fig. 14

and 17 and (26). If one considers two principal stresses in a plane parallel to the surface, then

$$\epsilon(\alpha) = K(\alpha)\sigma_1 + K(\alpha + 90^\circ)\sigma_2$$

where for simplicity the value z is taken as the full depth of the hole, and α is measured from the direction of the maximum stress σ_1 , (26). This procedure may give satisfactory results for the stress distribution close to the surface; however, the method is not accurate because the initial assumption for the strain change with a small hole depth increment is incorrect. The reason for this is shown in Fig. 22, see also (27), page 161.

The "Finite Element Method" (FEM) has been utilized by Schajer (27) to determine relaxations more accurately. A cross-sectional view before hole drilling is shown in Fig. 23, and the superposition of loadings to find the strain relaxation that occurs with drilling is shown in Fig. 24. The values of A_2 and B_2 for various hole depths calculated by the finite element method are compared with measured values in Fig. 25, where r_m denotes the mean gauge radius. Figure 26 shows the variation with hole depth of the dimensionless constants C_1 and C_2 , calculated by FEM for different hole diameters. The theoretical values of C_1 and C_2 , shown by the dashed lines, are approached asymptotically at large hole depths. A typical element mesh is shown in Fig. 27.

A power series method is applied to assess the variation of stress with depth (27). An approximate solution can be found using strain responses to unit power series stress fields calculated by the finite element procedure. The power series method is based on the possibility of a decomposition of an arbitrary stress profile into a series of stress profiles, see Fig. 28. It is known that an arbitrary stress field can be resolved into biaxial and shear stress components. Consider first the biaxial component, where the variation with depth from the surface is $\sigma_b(z)$. It is assumed that the unknown stress distribution can be expanded into a power series with undetermined coefficients b_i , $i = 0, 1, 2, \dots$

$$\sigma_b(z) = b_0 + b_1 z + b_2 z^2 + \dots$$

see Fig. 28(a-d). Then, assuming isotropy and homogeneity of the material, the surface response (surface strain) to relaxation of stresses at depths less than z is

$$\epsilon_b^z = b_0 \lambda_0(z) + b_1 \lambda_1(z) + b_2 \lambda_2(z) + \dots$$

where $\lambda_i(z)$ are the strain responses to unit power series fields z^i see Fig. 28(e-h). These responses can be calculated by the finite element method, and the coefficients b_i can be determined by a least squares minimization of error between ϵ_b^z as measured and ϵ_b^z as calculated from the above expansion. A similar calculation can be done for the shear stress component $\sigma_s(z)$.

The following describes measurement of a non-uniform residual stress field in practice.

First, a set of strain readings must be taken from each of the gauges for a series of hole depth increments; these readings are denoted by ϵ_1^z , ϵ_2^z , and ϵ_3^z . For a 45° rectangular rosette, the biaxial and shear components of strain are

$$\epsilon_b^z = \frac{1}{2} [\epsilon_1^z + \epsilon_3^z]$$

and

$$\epsilon_s^z = -\frac{1}{2} (2\epsilon_2^z - \epsilon_1^z - \epsilon_3^z)^2 + (\epsilon_1^z + \epsilon_3^z)^2 \text{ }^{1/2}$$

From ϵ_b^z and ϵ_s^z , the two stress profiles, $\sigma_b(z)$ and $\sigma_s(z)$, are estimated by the power series procedure. Then $\sigma_{\max}(z)$ and $\sigma_{\min}(z)$ (two principal stress profiles) are calculated using the relationships

$$\sigma_{\max}(z) = \sigma_b(z) + \sigma_s(z)$$

and

$$\sigma_{\min}(z) = \sigma_b(z) - \sigma_s(z) .$$

For reliable results, the power series must be truncated to two terms (27), so only two equations:

$$\sigma_b(z) = b_0 + b_1 z$$

and

$$\epsilon_b(z) = b_0 \lambda_0(z) + b_1 \lambda_1(z)$$

should be considered, where the unit responses $\lambda_0(z)$ and $\lambda_1(z)$ are calculated from the constants C_1 and C_2 given in Table 3.

Schajer's paper shows that finite element calculations can be successfully applied in association with measurements of residual stresses. Calculated calibration curves for a uniform stress field, see Fig. 25, agreed to within 5% of the experimentally determined values. For non-uniform stress fields, however, the finite element approach has not yet been experimentally verified.

2. Experimental Techniques of Hole Drilling

To obtain relieved radial strains ϵ_1 , ϵ_2 and ϵ_3 at points P_1 , P_2 and P_3 , respectively, see Fig. 18, a hole must be machined. Several machining techniques have been investigated and have been reported to be suitable for hole-forming:

- a) End mill, carbide drills and modified end mills, see Figs. 29 and 30, (24, 26, 28, 31)
- b) High speed drilling, developed at Ontario Hydro (32)
- c) Abrasive jet machining, see Figs. 31 and 32
- d) Electric discharge machining, employed extensively at Marchwood Engineering Laboratories (19, 25)

The strain readings ϵ_1 , ϵ_2 and ϵ_3 must be obtained from each gauge before the machining operation starts, and at intervals as the hole depth is increased incrementally. The increments should be 10% of the total depth, or smaller, but not less than 0.005 in. Since any residual stress created by the machining technique selected will adversely affect the accuracy of results, an assessment of strain induced by machining is advisable, see Fig. 33.

STATUS OF PMRL WORK

1. Experimental

a) Stress Measurement by Hole Drilling

Residual stress measurements have been made at PMRL by hole drilling since December 1979. Measurements of residual stresses by parting-out method and hole-drilling technique at several locations on a series of

pipe sections from commercial mills have been reported as part of the PMRL project on linepipe evaluation (33). It was concluded as a result of this work that there was good agreement between residual stress values measured by the two different strain gauge procedures.

Currently, work is being carried out to measure the residual stress distribution in a tapered cantilever beam subjected to bending as shown in Fig. 34. Results obtained by hole drilling will be compared with surface stresses measured by X-ray diffraction and with stresses calculated from bending strains measured by control gauges.

b) Stress Measurement by X-Ray Diffraction

According to Mitchell, stress measurement by X-ray diffraction has been carried out in the Physical Metallurgy Research Laboratories since 1973. The initial procedure used a standard diffractometer, modified for Rowland focusing with a tilted specimen, and provided stress measurement on small (1.5 cm x 1.5 cm) specimens using the multiple exposure method (34).

In 1975 a diffractometer with twin position sensitive detectors capable of measuring stresses on large specimens by the single exposure technique was designed and constructed in CANMET (35). This instrument uses a scanning X-ray tube and two fixed, adjustable, solid state Si(Li) detectors (see Fig. 35 and 36) and can accommodate specimens up to 20 kg. With this instrument, a variety of investigations have been carried out including

- i) measuring stress distribution over welds in HY 130 steel and relating this to the stress corrosion cracking behaviour (36);
- ii) determining the variation of stress with depth in a stainless steel overlay on a ferritic steel plate (37); and
- iii) measuring the stress variation over a cross-section of quenched and tempered steel rail in a study of shelling cracks developed during service (38).

A portable version of the dual detector scanning diffractometer has been designed, that is capable of collecting the full diffraction line simultaneously. The speed of the instrument is estimated to be 50 times that of a conventional diffractometer. The portable diffractometer is designed for stress measurement on engineering structures in the field. A prototype instrument is under construction and scheduled for field testing in 1984.

2. Analytical

Practical tests of the power series procedure described by Schajer (27), will be carried out with strain data obtained from experiments with a cantilever beam. The results in Tables 3 and 4 are for specimens which are deep compared with gauge dimensions, depth $>2.5 r_m$, (26). Therefore, a cantilever beam of thickness 0.275 in. will be investigated, because strain readings will be taken from the strain-gauge rosette type 062 RE whose mean radius, r_m , equals 0.101 in. ($2.5 r_m = 2.5 \times 0.101 \text{ in.} = 0.2525 \text{ in.}$). Moreover, to investigate the effect of specimen thickness, three other cantilever beams of thicknesses 0.130 in., 0.200 in., and 0.350 in. will be used. The results will be compared with the theoretically calculated non-uniform stress distribution generated by the known bending moments.

Thus, results from three sources: two experimental techniques, and a theoretical analysis, will be compared. This should give a good assessment of the value of the hole-drilling technique combined with the finite element method for measuring non-uniform residual stresses in metals.

ACKNOWLEDGEMENTS

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Table 1 - Relaxation and measurement techniques for different methods

Method	Relaxation technique	Measurement technique
Layer removal	Slicing, milling, grinding, lapping, chemical etching, electropolishing	Electrical resistance strain gauges, arc height, optical interference
Boring and turning	Boring, turning, combined boring and turning	Electrical resistance strain gauges
Hole machining, trepanning	Hole drilling, air abrasion, electric discharge, rotary cutting, overlapping holes	Electrical resistance strain gauges, brittle coatings
Parting-out	Cutting operations-sawing, sectioning	Electrical resistance strain gauges
Electromagnetic: Barkhausen, Magnetic	N/A*	Noise analysis, Reversible effective permeability,
Ultrasonic	N/A	Wave velocity, shear-wave birefringence, dispersion.
X-ray diffraction	N/A	Back reflection
Indentation	N/A	Hardness test
Stress corrosion	Corrosive agents	Relation between time-to-cracking and stress

*N/A - Not applicable

Table 2 - Comparison of methods

Method	Best suited to	Dimensional measurements	Precision	Known source of large error
Layer removal	Macro stresses - precise measurement of surface stresses and stress gradients	2D	Very accurate results from primary and secondary layer removal	N/A*
Boring and turning	Macro stresses - precise measurement of surface stresses	3D	Small error due to combined boring and turning	Steep stress gradient through the wall of a tube
Hole machining, trepanning	Macro stresses - subsurface average stresses	2D	Small error; trepanning more sensitive than hole machining	Stress gradient steep at surface
Parting-out	Macro stresses - average stresses in large parts	2D	Accurate average stresses	Stress gradient steep and changing
Electromagnetic	Macro stresses - measurement of subsurface stresses	2D	Excellent agreement between magnetically and mechanically measured stresses	N/A
Ultrasonic	Macro and micro stresses - measurement of surface stresses	2D (3D in perspective)	Small error	Cold-work and texture-induced birefringence, dislocations, anisotropy
X-ray diffraction	Macro and micro stresses - precise measurement of surface stresses	2D	Small error with correct technique	Bad focusing, cold-working, surface condition
Indentation	Macro stresses - mainly qualitative, average subsurface stresses	N/A	Unable to distinguish between uniaxial and biaxial stress states	Small changes in hardness are produced by large changes in stress
Stress corrosion	Macro stresses - mainly qualitative, surface stresses	2D	Depends on the applied fracture-mechanics analysis	Uncontrolled changes in composition of the metal, corrodents and the ambient temperature. Anisotropy.

Table 3 - Dimensionless constants C_1 and C_2 for uniform stress field.
After Schajer (27)

Hole depth	0.25	0.30	Constant C_1 Hole radius		0.45	0.50
			0.35	0.40		
0.1	-0.018	-0.026	-0.035	-0.049	-0.059	-0.081
0.2	-0.041	-0.057	-0.077	-0.104	-0.132	-0.172
0.3	-0.059	-0.083	-0.111	-0.148	-0.191	-0.233
0.4	-0.070	-0.099	-0.134	-0.174	-0.221	-0.265
0.5	-0.077	-0.108	-0.144	-0.188	-0.234	-0.283
0.6	-0.079	-0.111	-0.148	-0.192	-0.239	-0.288
0.7	-0.079	-0.111	-0.148	-0.191	-0.238	-0.287
0.8	-0.078	-0.110	-0.146	-0.189	-0.234	-0.283
0.9	-0.076	-0.107	-0.143	-0.185	-0.230	-0.278
1.0	-0.075	-0.105	-0.139	-0.181	-0.226	-0.272
Hole depth	0.25	0.30	Constant C_2 Hole radius		0.45	0.50
			0.35	0.40		
0.1	-0.035	-0.052	-0.069	-0.092	-0.120	-0.150
0.2	-0.080	-0.110	-0.144	-0.187	-0.236	-0.292
0.3	-0.124	-0.171	-0.221	-0.286	-0.350	-0.428
0.4	-0.158	-0.218	-0.282	-0.357	-0.436	-0.520
0.5	-0.181	-0.250	-0.323	-0.407	-0.490	-0.576
0.6	-0.196	-0.270	-0.350	-0.437	-0.524	-0.610
0.7	-0.205	-0.282	-0.365	-0.455	-0.544	-0.632
0.8	-0.209	-0.288	-0.373	-0.466	-0.554	-0.642
0.9	-0.211	-0.290	-0.377	-0.467	-0.559	-0.646
1.0	-0.211	-0.291	-0.378	-0.468	-0.560	-0.648

Table 4 - Dimensionless constants C_1 and C_2 for a linear stress field.
After Schajer (27)

Hole depth	0.25	0.30	Constant C_1 Hole radius		0.45	0.50
			0.35	0.40		
0.1	-0.0007	-0.0011	-0.0015	-0.0020	-0.0024	-0.0031
0.2	-0.0036	-0.0050	-0.0065	-0.0087	-0.0108	-0.0140
0.3	-0.0071	-0.0098	-0.0130	-0.0170	-0.0205	-0.0245
0.4	-0.0102	-0.0140	-0.0183	-0.0233	-0.0279	-0.0321
0.5	-0.0123	-0.0169	-0.0216	-0.0270	-0.0318	-0.0361
0.6	-0.0134	-0.0178	-0.0229	-0.0279	-0.0325	-0.0367
0.7	-0.0131	-0.0173	-0.0221	-0.0268	-0.0311	-0.0346
0.8	-0.0120	-0.0158	-0.0201	-0.0243	-0.0279	-0.0309
0.9	-0.0106	-0.0140	-0.0175	-0.0209	-0.0241	-0.0266
1.0	-0.0089	-0.0117	-0.0145	-0.0173	-0.0197	-0.0220
Hole depth	0.25	0.30	Constant C_2 Hole radius		0.45	0.50
			0.35	0.40		
0.1	-0.0016	-0.0025	-0.0035	-0.0045	-0.0056	-0.0066
0.2	-0.0070	-0.0097	-0.0128	-0.0166	-0.0202	-0.0250
0.3	-0.0159	-0.0218	-0.0279	-0.0355	-0.0415	-0.0479
0.4	-0.0256	-0.0348	-0.0446	-0.0550	-0.0638	-0.0718
0.5	-0.0344	-0.0466	-0.0595	-0.0717	-0.0850	-0.0950
0.6	-0.0417	-0.0558	-0.0713	-0.0860	-0.1000	-0.1106
0.7	-0.0465	-0.0625	-0.0795	-0.0956	-0.1093	-0.1207
0.8	-0.0490	-0.0666	-0.0847	-0.1010	-0.1153	-0.1269
0.9	-0.0504	-0.0683	-0.0873	-0.1037	-0.1187	-0.1305
1.0	-0.0506	-0.0686	-0.0881	-0.1045	-0.1197	-0.1317

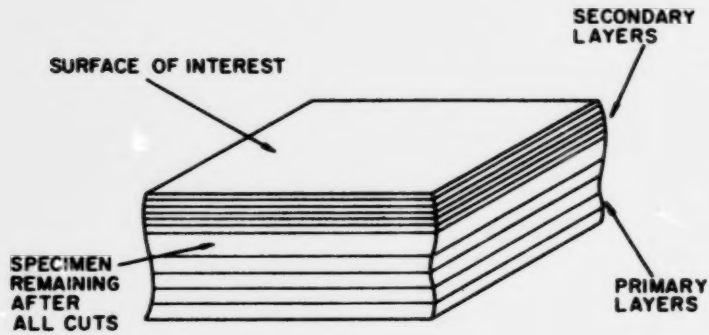


Fig. 1. Primary and secondary layers in plate after grinding and slicing.
(neg 6445)

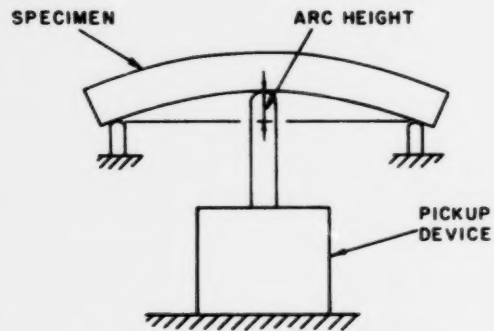


Fig. 2. Schematic diagram of curvature (arc height) measurement. (neg 6461)

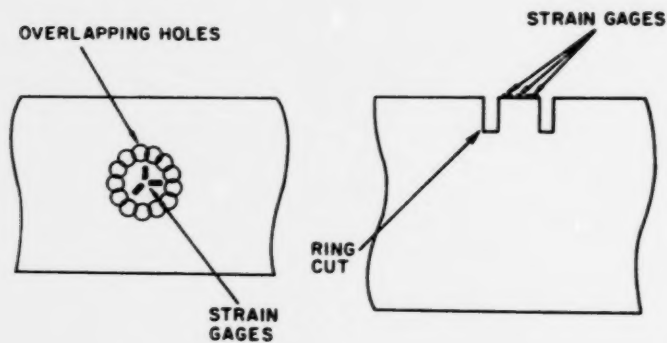


Fig. 3. Schematic of the strain-gauge arrangement inside the ring cut.
(neg 6444)

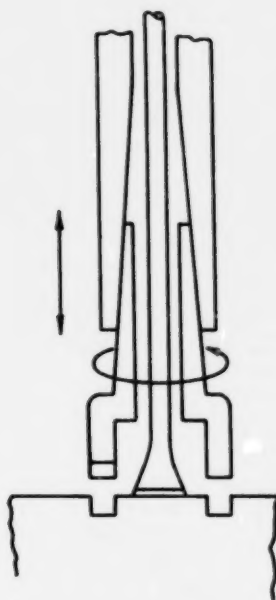


Fig. 4. Rotary cutting. After Downe and Fidler (19). (neg 6443)



Fig. 5. Electric discharge machining (19). (neg 6448)

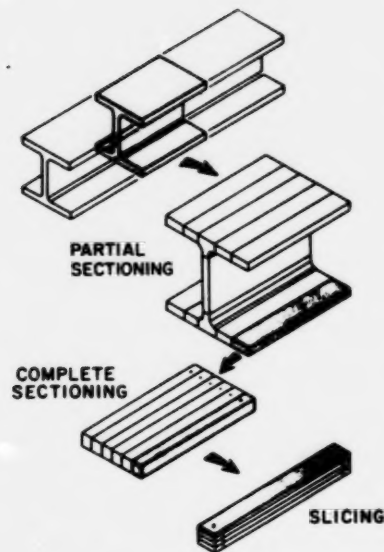


Fig. 6. Parting-out of bar; steps in the sectioning technique. After Tebedge, Alpsten, and Tall (5). (neg 6442)

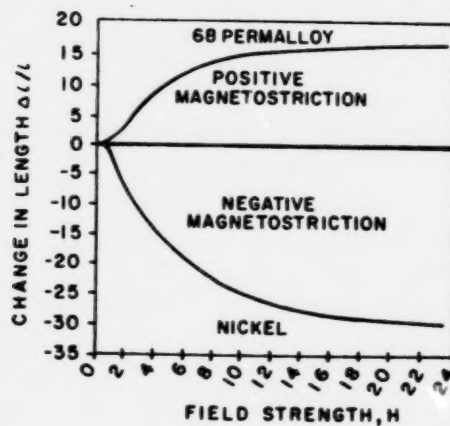


Fig. 7. Variation of length with field strength, showing positive and negative magnetostriction for 68 Permalloy and nickel respectively. After Encyclopaedia Britanica. (neg 6457)

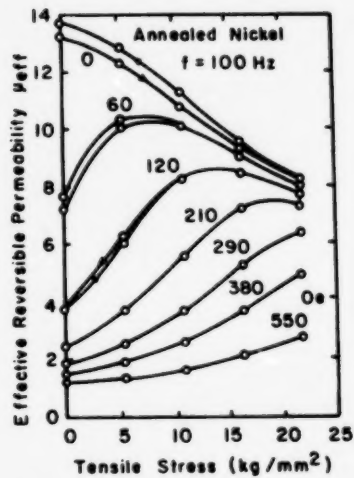


Fig. 8. Variation of μ_{eff} of a solid nickel bar with applied stress at 100 Hz. Numbers on curves give biasing field. After Abuku and Cullity (7). (neg 6455)

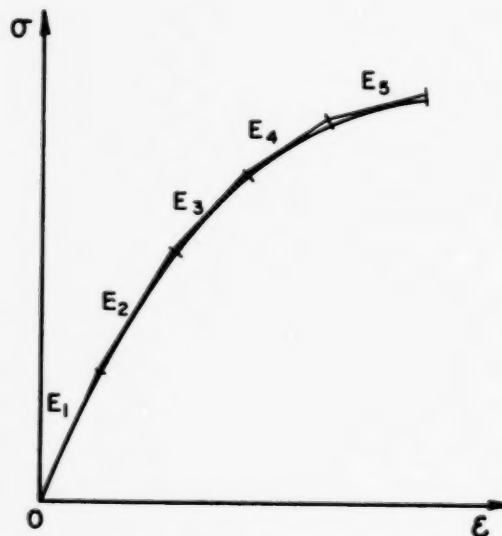


Fig. 9. Non-linear stress-strain relationship approximated by linear segments. Material constants, E_i , $i = 1, \dots, 5$, determine slope of the segments. (neg 6454)

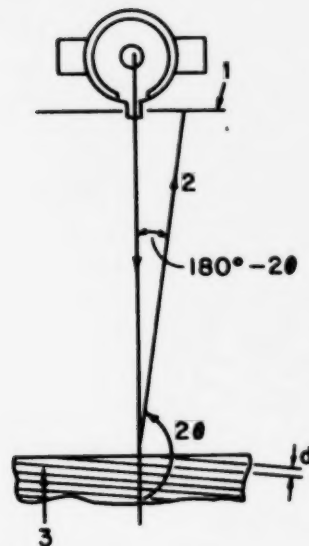


Fig. 10. Principle of back reflection technique for strain measurements using X-ray diffraction. Angle 2θ varies for a particular set of planes with lattice strain. 1 - film (or diffractometer); 2 - diffracted ray; 3 - reflecting planes of atoms. (neg 6454)

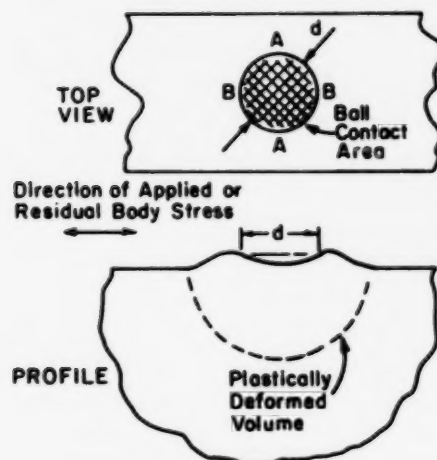


Fig. 11. Schematic of indentation geometry. After Underwood (11). (neg 6441)

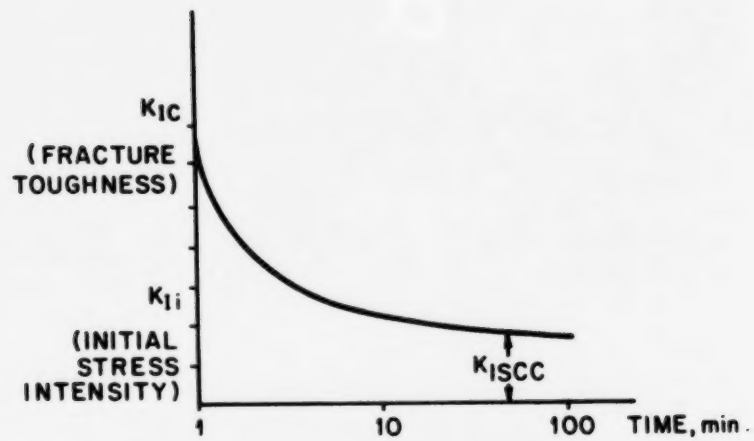


Fig. 12. Stress corrosion test data showing dependence of time-to-failure on initial stress intensity factor K_I . After Dieter (12). (neg 6446)

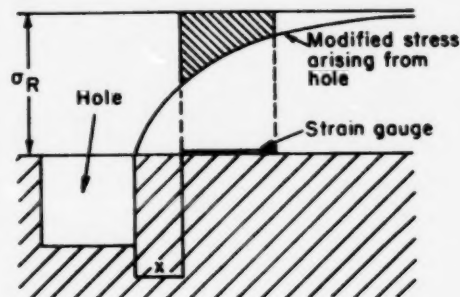


Fig. 13. Principle of hole-drilling technique. σ_R is the residual stress. (neg 6460)

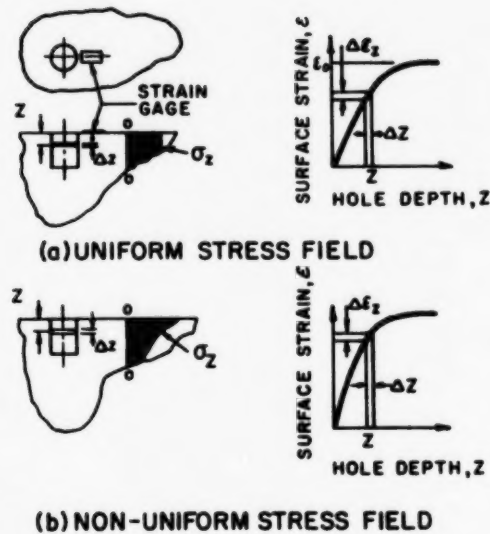


Fig. 14. Relationships between surface strain and hole depth for uniform and non-uniform stress fields. After Kelsey (28). (neg 6459)

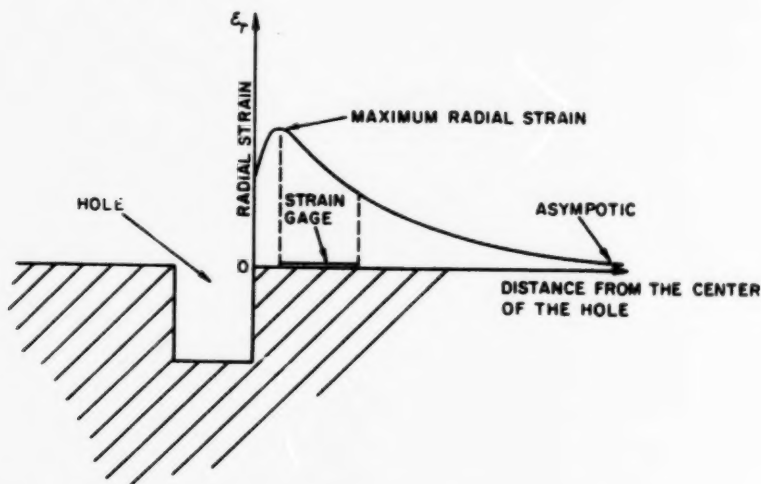


Fig. 15. Variation of relieved strains with distance along a principal axis from the center of the drilled hole, for uniaxial residual stress. (neg 6439)

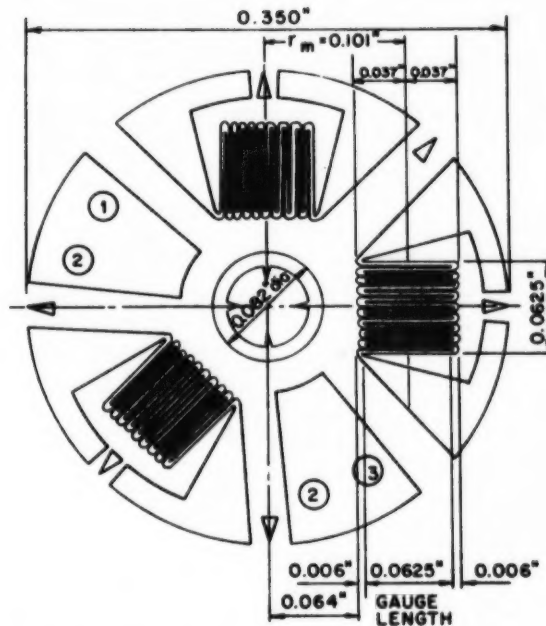


Fig. 16. 45° rectangular rosette for residual stress measurement. After Beaney (16). (neg 6438)

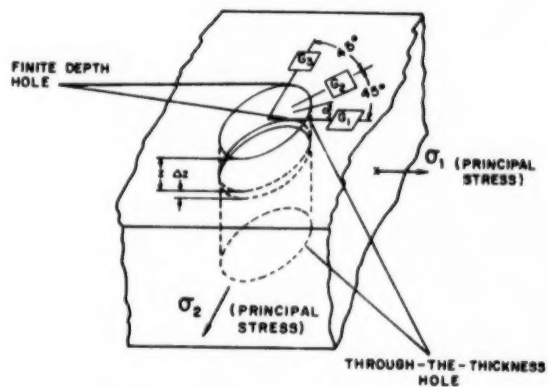


Fig. 17. Part of an infinite stressed plate with two kinds of holes. (neg 6469)

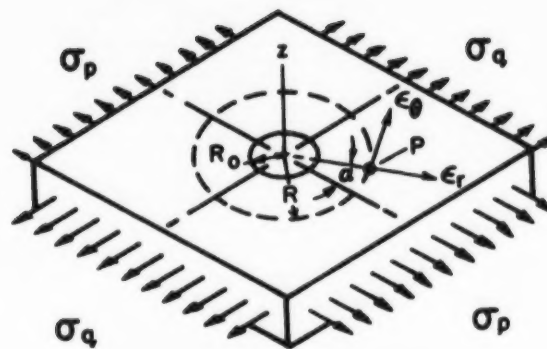


Fig. 18. Strain relaxation at point P due to the introduction of a hole (24).
(neg 6458)

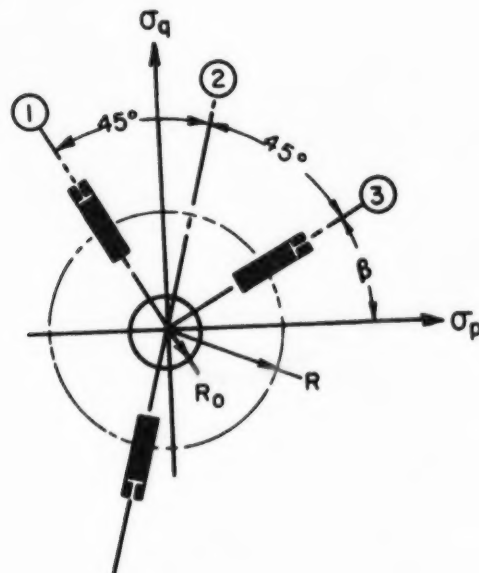


Fig. 19. Strain gauge rosette arrangement for determining residual stresses
(24). (neg 6437)

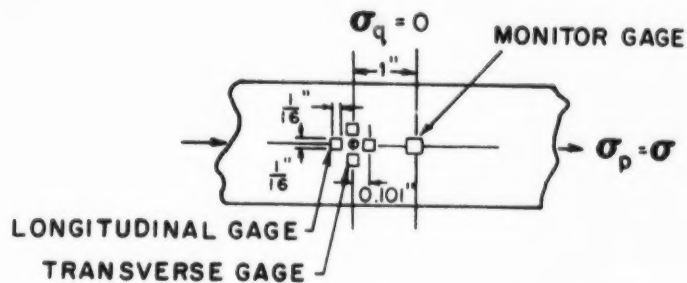


Fig. 20. Double 0-deg, 90-deg rosette (26). (neg 6468)

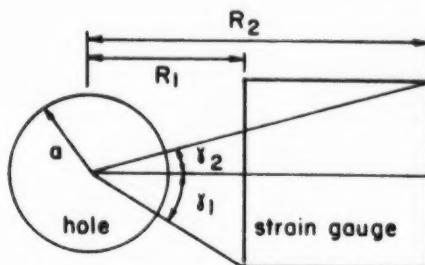


Fig. 21. Strain gauge geometry (27). (neg 6467)

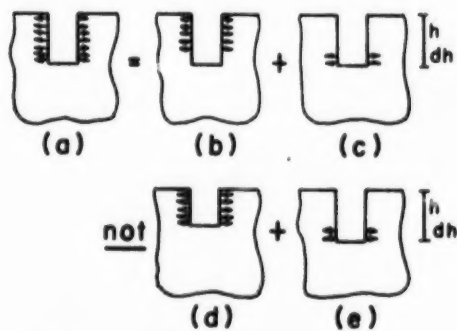


Fig. 22. Superposition of loadings due to stresses at different depths (27). (neg 6449)

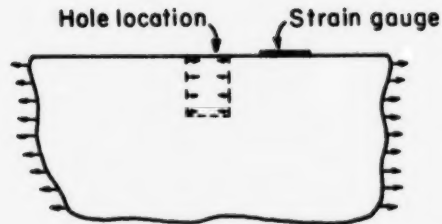


Fig. 23. Cross-section of strain gauge area before the hole is drilled (27).
(neg 6466)

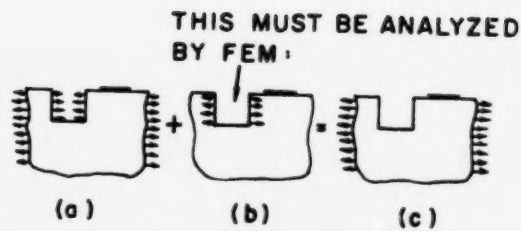


Fig. 24. Superposition of loadings to find the strain relaxation arising from drilled hole (a) original stresses, (b) stress change owing to hole drilling, (c) final stresses (27). (neg 6464)

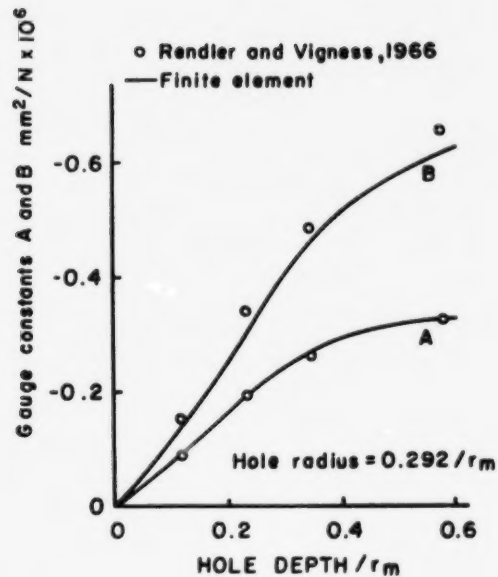


Fig. 25. Constants A_2 and B_2 calculated by the finite element method compared with the experimental results of Rendler and Vigness (26) for a uniform stress field. (neg 6465)

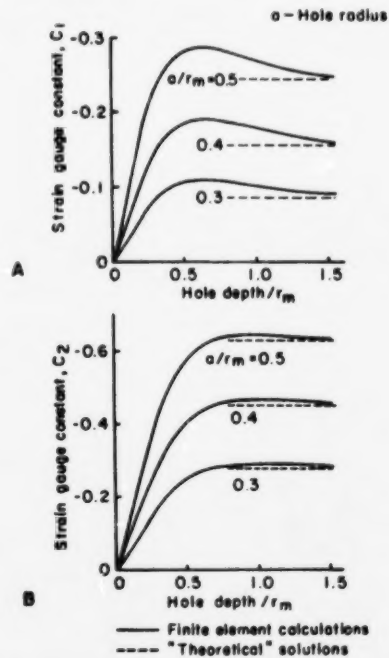


Fig. 26. Calculated constants (a) C_1 , (b) C_2 , for a uniform stress field with the strain gauge rosette and a square-ended hole (27). (neg 6453)

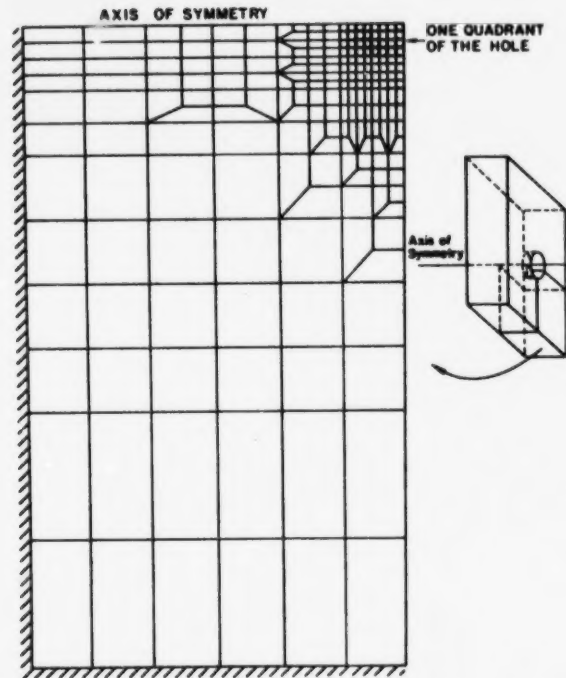


Fig. 27. Finite element mesh; private communication from G.S. Schajer.
(neg 6447)

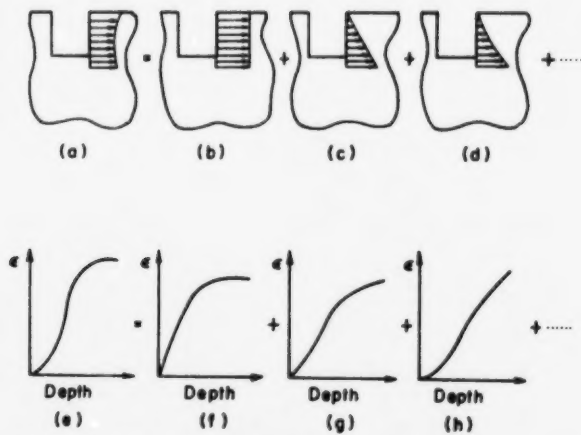


Fig. 28. (a), (b), (c), (d) Resolution of an arbitrary stress profile into a power series of stress profiles. (e), (f), (g), (h) Corresponding relaxed strain versus depth (27). (neg 6462)

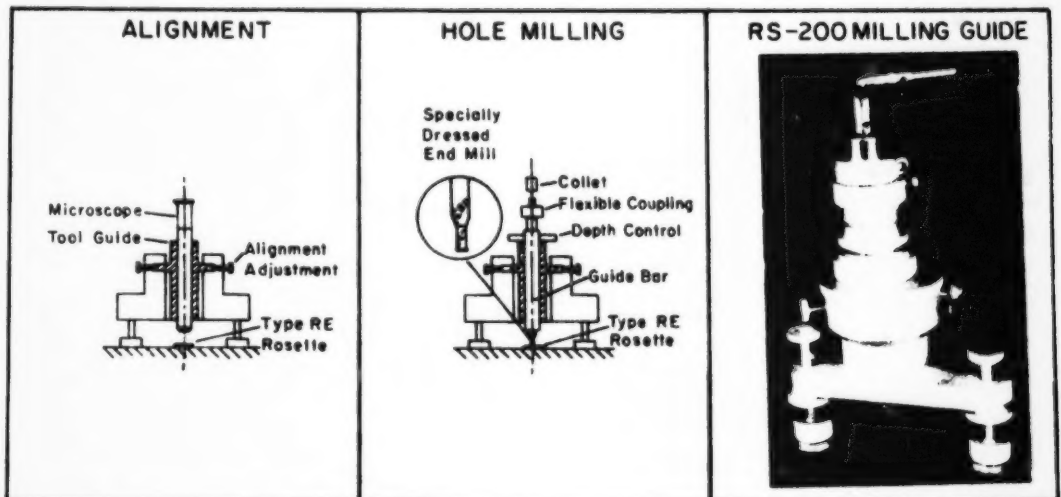


Fig. 29. Procedure and equipment for machining a precisely located, straight hole. After Photolastic Inc. (24). (neg 6510)

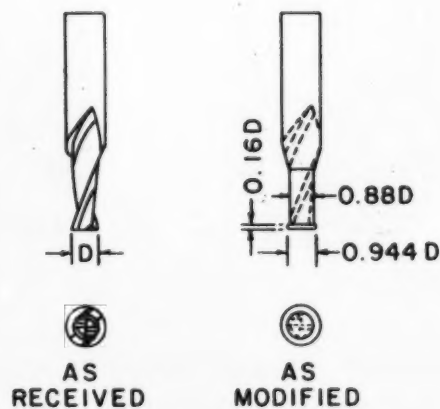


Fig. 30. End-mill modification. After Rendler and Vigness (26). (neg 6463)

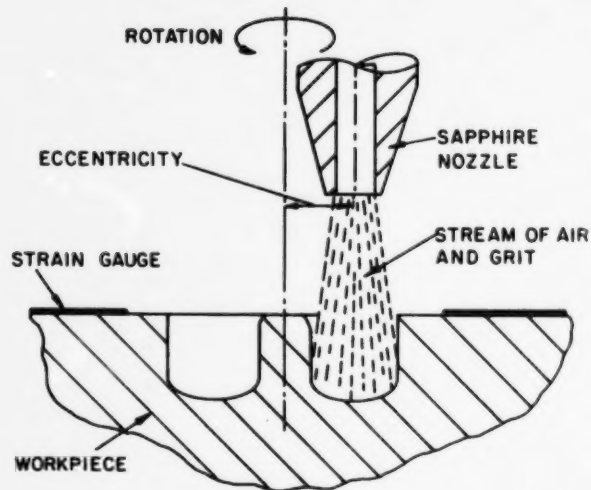


Fig. 31. Abrasive jet machining using a rotating nozzle. After Beaney (18).
(neg 6446)

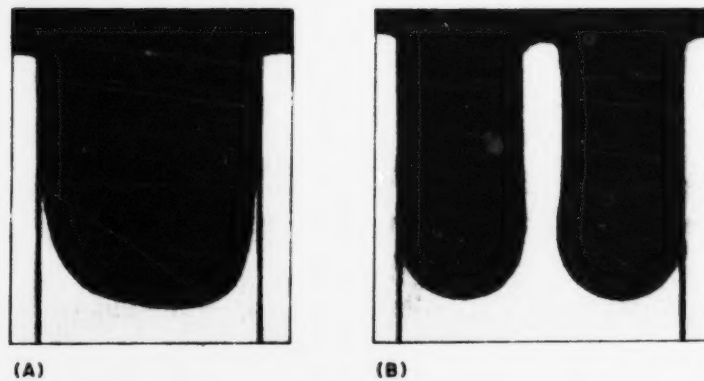


Fig. 32. (a) Hole drilled using a stationary nozzle.
(b) Hole drilled using a rotating nozzle.
After Beaney (18). (neg 6450)

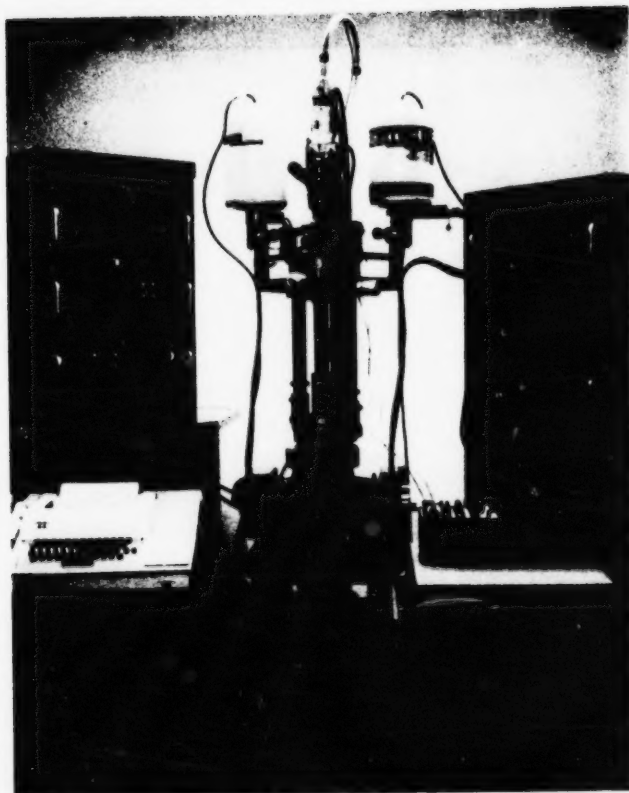


Fig. 35. Stress diffractometer. (neg 6239)

DUAL DETECTOR DIFFRACTOMETER

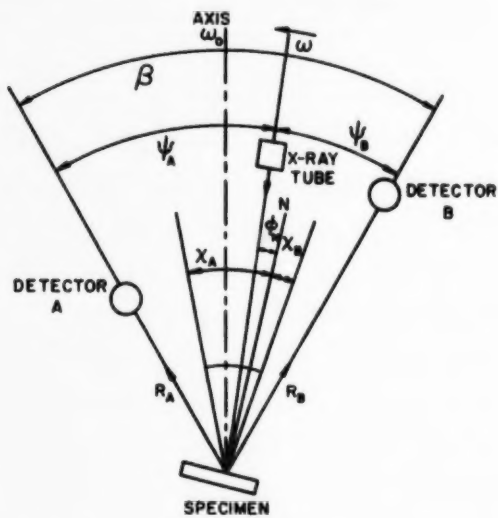


Fig. 36. Equatorial plane of the stress diffractometer (36). (neg 6240)

APPENDIX

In May, 25-27, 1981, CEA organized a symposium on "Experimental Determination of Residual Stresses", which was held at Ontario Hydro Research Division, Toronto.

The objectives of this symposium were:

- i) to investigate general methods of the experimental determination of residual stresses with a special emphasis on hole drilling as well as sectioning;
- ii) to develop a capability, based upon the results of the above investigations, to measure 2-D residual stresses varying with specimen depth and determine 3-D residual stresses; and
- iii) to establish the validity and accuracy of methods of experimental residual stress determination by comparing experimental results with known theoretical results.

The symposium was based on seven papers prepared by the Central Electric Generating Board (CEGB), U.K. (15-21). Most of the program was devoted to developments and applications of hole machining; the two hole forming techniques, hole-drilling and air abrasion, were presented in detail, with special emphasis on the latter. The principle of the method and its application were described in (15); it was concluded that the method has good reliability and, subject to the choice of technique for hole forming, can give an accuracy better than $\pm 10\%$ for uniform stress fields. The effects of strain gauge position and orientation on the apparent distributions of residual stress across a transition weld between materials with differing coefficients of thermal expansion were demonstrated in (17). The measured stresses were compared with theoretical distributions, and the performance of the different methods in measuring stress across steep gradients was evaluated. This work confirmed the capability of the hole-machining method in detecting steep gradients associated with discontinuities such as fusion welds.

Papers (16) and (18) trace the development of the air-abrasive technique for making holes and its subsequent calibration. From the results of calibration, the accuracy of the system was predicted. The technique, using the CEGB rotating nozzle equipment described in (18), has gained wide acceptance for measuring residual stresses in any steel with an accuracy of better than $\pm 8\%$. This technique appears to be stress free, i.e., no machining stresses are induced during hole-forming. In contrast, hole drilling by

milling cutters or drills is of no use on stainless or high strength steel because of large stresses induced during machining.

Steps involved in measuring residual stresses by trepanning, using electrical discharge machining, are presented in (19) in the form of an illustrated manual. This should be of particular value to technicians. The information is based upon procedures established at Marchwood Engineering Laboratories.

The applications of finite element analysis to residual stress measurement are described in (16), (20), and (21) with reference to air abrasion, trepanning, and turning, respectively. Beaney (16) made some finite element calculations using axisymmetric elements only, in order to examine the influence of hole shape on his calibration constants, but his final results are based on experimental measurements. Because the analysis was limited to axisymmetric problems, only equi-biaxial stress fields could be studied. Finite element calculations also have been used for predicting residual stresses in welded structures. Fidler (21) established a method permitting him to determine the complete 3D distribution of residual stress in a main steam-pipe weld in the as-welded condition.